



Research article

The Iceberg Model of Change: A taxonomy differentiating approaches to change

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ABSTRACT

Change is a ubiquitous phenomenon, but different scientific communities conceptualize change differently, which hampers conceptual clarity. This conceptual paper, which is based on a review of the literature on change, addresses this problem by developing the 'Iceberg Model of Change'. This framework distinguishes three approaches to change: objectification, distinction, and unfolding. The objectification approach treats processes of change as things with symbolic properties, which can be used to steer societal and political discourse, reveal thematic relationships across studies, and emphasize the significance of work. This approach also tends to consider change as a variable (dependent or independent) that can be used to understand antecedents and consequences. The distinction approach conceptualizes change as a series of discrete states of an entity or system at multiple points in time or as phases, enabling comparison of those states. The unfolding approach considers how change processes develop, including the complex, interrelated mechanisms underpinning change. Here, line graphs, visualizations of interaction mechanisms, and trajectories are used to capture change. This framework contributes to research, a) by enabling a comprehensive consideration of change phenomena, b) by promoting interdisciplinary collaboration when project partners differ in their assumptions about change, and c) by emphasizing the need for methodological reflexivity.

1. Introduction

Change is a ubiquitous phenomenon. It has already played a central role in ancient Greek philosophy, such as the work of Heraclitus, Plato, and Aristotle [1]. Over the centuries, the idea that change is an essential aspect of many phenomena has proliferated in various scientific disciplines, including medicine [2], climate science [3], geography [4], organization studies [5], employment research [6], material science [7], and many more. As such, studying change is recognized as crucial in both research and practice. Conceptualizations of change, however, often develop within specific scientific communities [8], leading to different approaches and understandings of change. Against this backdrop, there is a need to articulate approaches to change to foster conceptual clarity. This

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becomes particularly important when scholars from different disciplines come together, as different approaches to change build on varying implicit onto-epistemological assumptions. Divergent yet implicit assumptions could hamper collaboration because of potential misunderstandings [9–11].

Thus, this article aims to sensitize scholars to different approaches to change. To accomplish this, we use an extensive review of the literature to develop a framework that differentiates three approaches. First, the *objectification approach* treats processes of change as things to which properties can be assigned. This approach considers change as a symbol, which can be used to steer societal and political discourse, reveal thematic relationships across articles, and emphasize the significance of work. Moreover, the objectification approach often considers change as an independent or dependent variable that can be used to understand antecedents and consequences. Second, the *distinction approach* conceptualizes change as a series of discrete states or phases of an entity or system at multiple points in time. This approach is suitable to make comparisons across states and phases. Third, the *unfolding approach* considers how change processes develop, including the interrelated mechanisms that unfold over time and interact in complex ways underpinning change. We argue that each of the three approaches has its merits, and they are not mutually exclusive but entail an increasing depth of engagement with change: the objectification approach treats change like a black box, which is opened as we consider the other approaches. We, therefore, relate those approaches in a taxonomic framework, which we label the ‘Iceberg Model of Change’ (see Fig. 1).

The ‘Iceberg Model of Change’ is the core contribution of this paper. The development of this framework has important implications for research. First, it enables a more comprehensive conceptualization of change, which can help scholars see their focal phenomena of interest in new ways. Second, we argue that our framework can support interdisciplinary collaboration about exploring phenomena in which change plays an important role (e.g., climate change). Because scholars from different disciplines often have varying assumptions about change, our framework enables common ground. Third, our framework has methodological implications, as each approach implies the application of different methods.

This article is structured as follows. First, we describe the methodological approach through which we developed the framework. Second, we describe the framework and detail examples from published research to substantiate our claims. Third, we discuss the implications for research. Fourth, we conclude with avenues for future research.

2. Method

Step 1 Identifying change papers. Building on the observation that change plays an essential role in many research disciplines, we obtained articles from the ‘Web of Science Clarivate Analytics’ database [12], searching for the term ‘change’ in the title and author keywords, and selecting highly cited articles (a selection criterion offered by the database). This search resulted in 4423 articles.

Step 2 Analyzing change topics. Because we wanted to identify phenomena in which change matters, we applied co-occurrence analysis to the dataset derived from Step 1. We used ‘VOSviewer’, a widely used tool in bibliometric analysis [13–15], to accomplish this. ‘VOSviewer’ applies a clustering function that assigns words to thematic clusters based on their co-occurrence in paper titles [16]. The more often two words occur together in article titles, the closer they are positioned to each other in the resulting network (see Fig. 2). This way, it is possible to identify broader topics in a dataset. We identified five main topics in which change plays an essential role. Each topic is highlighted in a different color in Fig. 2. The appendix provides detailed descriptions of these topics.

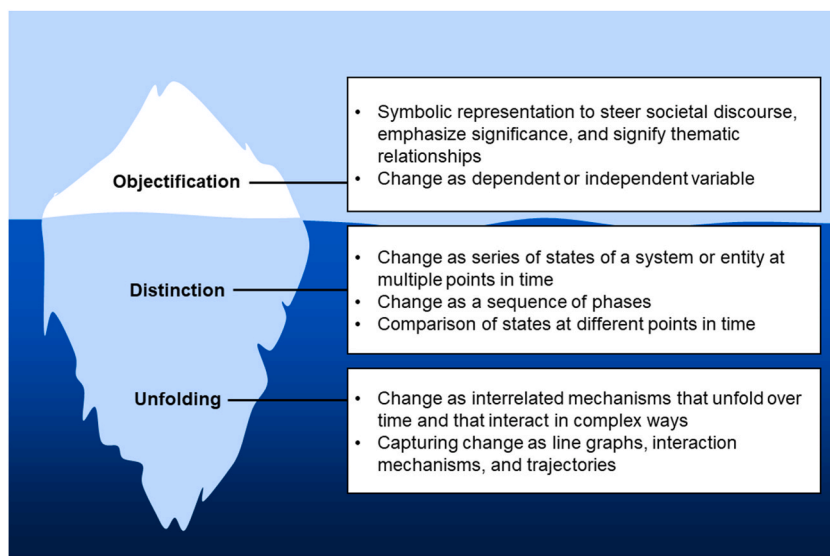


Fig. 1. The Iceberg Model of Change.

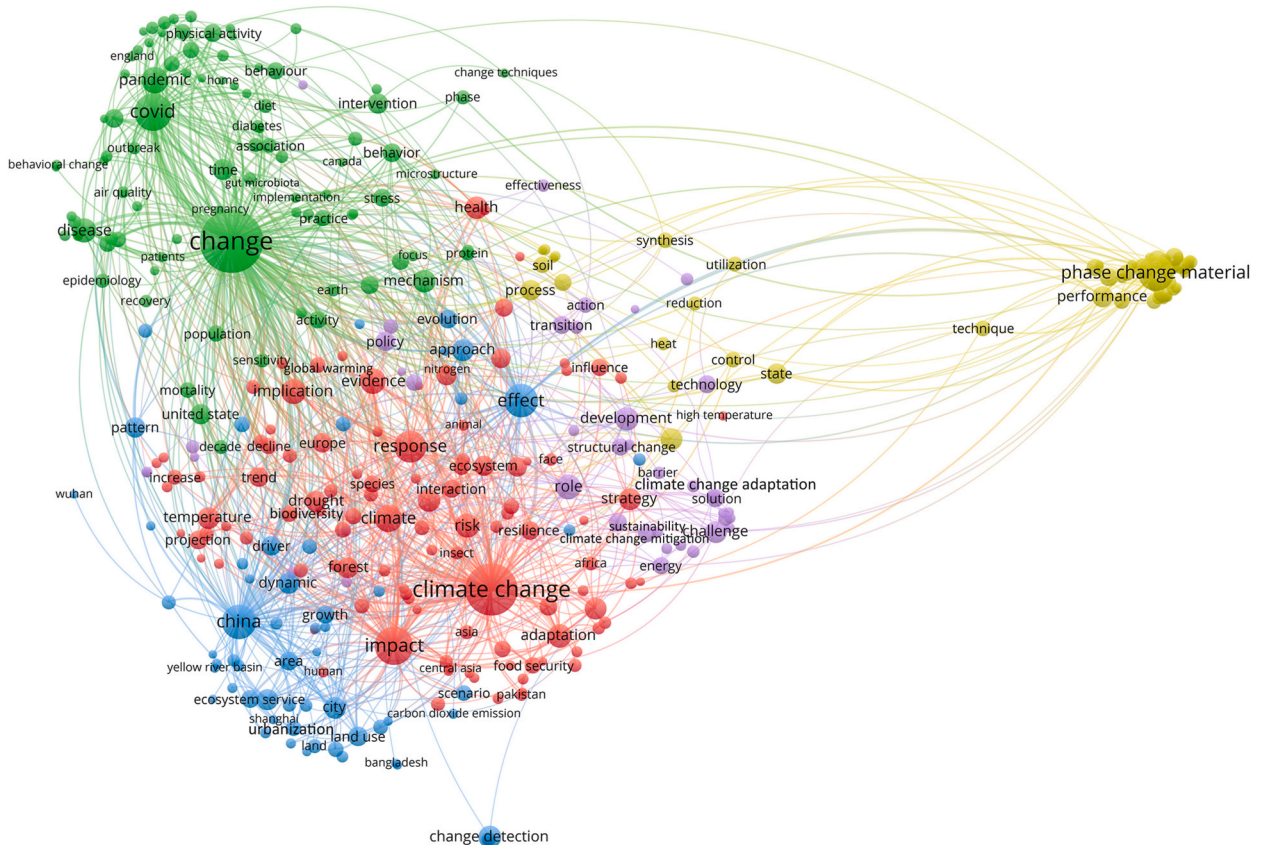


Fig. 2. Overview of phenomena in which change matters.

Step 3 Identifying change-related differences across papers. Step 2 helped us develop an overview of research that deals with change, but we realized that articles employ different assumptions about change. Thus, we started analyzing the 15 most highly cited publications in our dataset to identify different ways in which change is conceptualized. In an iterative process (involving multiple rounds) of (a) defining categories, (b) discussing and aligning them across members of the author team, and (c) applying the categories to further papers, we defined a set of categories that enabled us to characterize change in those articles. We increasingly incorporated more papers in our analysis until we reached a point of theoretical saturation [17]. In sum, we analyzed the 80 most highly cited papers in our dataset. Iterating through this process over several rounds, we uncovered three different approaches to change (i.e., objectification, distinction, and unfolding). As we crafted the textual description of the three approaches, we considered additional articles (e.g., popular change frameworks) that help to illustrate our arguments. The overview of change topics derived from Step 2 informed the incorporation of those additional articles.

3. Results: The Iceberg Model of Change

The central contribution of this article is to develop a taxonomic framework, which we label the ‘Iceberg Model of Change’ (Fig. 1). This taxonomy incorporates three approaches to change: the objectification approach, the distinction approach, and the unfolding approach. We use the iceberg metaphor because those approaches reflect increasing depth. While the objectification approach does not uncover the internal dynamics of change, the distinction and ultimately the unfolding approach reveal the internal dynamics of those processes. However, the iceberg metaphor also indicates that we do not consider those approaches as mutually exclusive: each approach focuses on a different aspect of change in a particular phenomenon, and thus those approaches should be seen as complementary. We next describe each approach in detail.

3.1. Objectification approach

Change as a symbolic representation. The objectification approach treats processes of change as ‘things’, often with a teleological connotation. A well-known example is the ‘1.5-degree pathway’, i.e., the aim of limiting human-made global warming to a maximum of 1.5 °C in the timespan from 1900 to 2100 [18]. Similarly, the ‘4 per mille’ goal refers to an annual increase of global soil organic matter stocks by 0.4 percent per year to compensate for emissions [19]. Other examples of the objectification approach cover

performance metrics of companies (e.g., increasing profit by 10 percent), public health initiatives (e.g., reducing the incidence of smoking-related diseases by 10 percent), and educational reforms (e.g., increasing high school graduation rates by 10 percent). In all those examples, the change process itself (e.g., global warming, performance increase, reduction of smoking-related diseases) remains black-boxed (i.e., scholars do not examine how it unfolds).

The objectification approach uses change as a symbol to strategically stress relevance and influence collective behavior. For instance, the ‘1.5-degree goal’ is loaded with symbolic meaning that steers societal discourses. As a consequence, politicians and researchers identify measures that may help to mitigate climate change [20]. Similarly, the term ‘climate change’ is often used to stress the relevance of scientific studies [e.g., 21–24]. Zarfl et al. [25], for instance, argue that climate change stimulates demands for renewable energy, which sets the ground for their study on hydropower dams. Hence, the authors use the notion of climate change to stress the relevance of their project. Moreover, scholars often lend significance to their studies by emphasizing the ever-increasing intensity of change, such as the increasing extensiveness of extreme events [26,27] or increasingly competitive market conditions [28]. Some scholars also use the term ‘global change’ to signify the overwhelming degree of change in our society [29–31].

Another purpose of the objectification approach is to situate work in a broader discourse, revealing thematic relationships among studies. Consider the following examples. First, ‘climate change’ serves as an umbrella term for studies on diverse topics such as permafrost carbon feedback [32], biodiversity [33], wildfires [34], or extinction risks [35]. Second, the term ‘urban development’ considers urbanization as a change process. Studies using this term cover the application of resilience theory in managing socio-ecological systems [36], the conversion of natural landscapes into built environments [37], biodiversity loss through urbanization [38], and inequalities through rapid urbanization [39].

Change as a dependent or independent variable. From a methodological point of view, the objectification approach tends to conceptualize change as a dependent or independent variable. Several studies consider change as a *dependent* variable. An example is the ‘Theoretical Domains Framework’ in implementation science, which lists a set of factors (e.g., knowledge, skills, role, and identity) that are expected to influence behavioral change [40]. In organization studies, dynamic managerial capabilities, such as managers’ abilities to sense environmental dynamics, are seen as antecedents to the strategic change of the organization [41]. Similarly, organizational change may be influenced by job crafting [42].

Studies also consider change as an *independent* variable. For instance, scholars examine the impact of climate change on various aspects such as wildfires [34], biodiversity [43], cyanobacterial blooms [44], river flows [45], rice supply [46], and bumblebee populations [47]. Other scholars examine how changes in technology drive transformations in employment [48], carbon emissions [49], sustainable practices [50], and healthcare practices [51], highlighting the influence of technological progress on shaping societal and economic domains.

3.2. Distinction approach

Change as a series of discrete events or phases. Adopting a distinction approach, scholars view processes of change as series of discrete states of systems or entities at different points in time. Neumann et al. [52], for instance, estimate the states of coastal populations at three points in time (i.e., 2000, 2030, and 2060). Hughes et al. [4] determined the states of coral reefs (i.e., their extent of bleaching) in 1998, 2002, and 2016. Similarly, Craddock et al. [53] examine how human health changes through behavioral change interventions. More specifically, they examine the states of the human body (i.e., hemoglobin and body weight) after 3, 6, 12, and 24 months following an intervention which targets diet and physical activity in patients with type 2 diabetes.

Using a distinction approach, scholars also describe the phases that are characteristic of particular change processes. In psychological research, multiple models describe behavioral and psychological changes as sequences of phases. Lewin [54], for instance, suggest that change occurs in three phases: unfreezing, moving, and freezing. Kübler-Ross [55] developed a model of grief, including the phases of denial, anger, bargaining, depression, and acceptance. Individuals may progress through those phases sequentially, but they may also go back and forth. Similarly, Kotter’s [56] eight-step model of change involves the following phases: creating a sense of urgency, building a guiding coalition, developing a vision and strategy, communicating the change vision, empowering broad-based actions, generating short-term wins, consolidating gains and produce more change, as well as anchor new approaches in corporate culture. In resilience research, the ‘Adaptive Cycle Model’ is another example of a phase-based approach, consisting of the steps of exploitation, conservation, release, and reorganization [57].

Comparing states at different points in time. Scholars often measure the states of an entity or system at multiple points in time. For instance, they examine mortality rates [58], bleaching degrees of coral reefs [4], land change [59,60], and forest areas [61] at different points in time. Consequently, scholars can compare those states. Neumann et al. [52], for instance, estimated coastal populations at three points in time, which can be used to identify trends. An example in the realm of education research is the longitudinal study conducted by Torres-Martín et al. [62], which investigates the implementation of the flipped classroom teaching method and its impact on improving academic performance. The study assesses student test scores, engagement levels, and graduation rates over several academic years to capture the effectiveness of the flipped classroom approach. By comparing these metrics across points in time, educators and researchers were able to discern trends in educational outcomes, providing valuable insights for adjusting teaching strategies.

3.3. Unfolding approach

Change as complex interactions, dynamics, and flow. The unfolding approach emphasizes the complex mechanisms and interactions that propel processes of change forward. The unfolding approach corresponds with the ‘Strong Process Ontology’ [63] in

organization studies. This idea, which originated in philosophy [64], goes beyond the assumption that change happens to entities but instead assumes that entities are temporary manifestations of processes of change. Hence, ontological priority is given to the change process rather than the entity that is being changed. This approach helps scholars to better understand how and why change occurs. These scholars, for instance, examine how organizational routines change and remain stable over time. Deken et al. [65] showed how actors incorporate novelty into routines, as they engage in iterative cycles of routine work, surfacing differences, and emerging consequences. In the realm of climate science, Seidl et al. [66] examined the direct, indirect, and interaction effects in the context of climate change-induced forest disturbance. These authors analyzed how climate change affects forest disturbances through various factors such as fire, drought, and insects by examining the complex interplay between these mechanisms. Wind disturbance, for example, can create favorable conditions for insect outbreaks, leading to increased impacts on forest ecosystems. In material science, Younsi and Naji [67] examine the dynamics of phase change materials integrated into brick walls aimed at improving the thermal performance of buildings. They explore the complex interplay of environmental conditions, phase changes in materials, and energy storage.

Capturing change as line graphs, interaction mechanisms, and trajectories. Several studies that adopt the unfolding approach visualize change as line graphs over time. For instance, the ‘Great Acceleration Graphs’ are a set of charts that show socio-economic trends and trends in the earth system over decades, including changes in population, water use, transportation, methane, surface temperature, and many more [68]. Pekel et al. [69] also show how global water coverage changes over time. They provide line graphs for water changes in multiple countries. Gössling et al. [30] provide graphs that show how global tourism changes over time, and they indicate how crisis events, such as the global economic crisis or the 9–11 terrorist attack, affected this change process.

Moreover, scholars adopting the unfolding approach visualize complex interaction mechanisms. System dynamics scholars, for instance, describe processes of change in causal loop diagrams or dynamic stock and flow diagrams [70]. These visualizations capture the complex feedback loops of the components of a system, which can be used to describe the internal dynamics of change. Littlejohns et al. [71], for example, used a causal loop diagram to explore the complex interactions influencing health promotion practices within a health system. This study identified virtuous and vicious feedback loops, illustrating how changes in one part of the system can influence health outcomes across the system. For example, the lack of leadership and policy directions reduces community participation and weakens health promotion practices. This leads to a vicious feedback cycle. Another example is the ‘Driver-Pressure-State-Impact-Response Framework’ (DPSIR) [72]. This framework suggests that drivers such as human behavior put pressure on the environment. These pressures change the state of the environment, which has biological, economic, and social impacts that lead to governmental and societal responses. The latter aspects close the loop by influencing drivers and pressures. The DPSIR framework can be used to describe the complex interactions that matter for environmental change. Relatedly, Steffen et al. [73] show possible tipping cascades that could lead the earth system to a hothouse earth pathway. The loss of the East Antarctic Ice Sheet, for instance, could influence thermohaline circulation, which could then transform the Amazon rainforest into a savanna.

Scholars adopting the unfolding approach also capture change by focusing on trajectories and pathways. In biology research, for instance, ‘Waddington’s Canalization’ [74] describes the evolution of phenotypes in development. The central idea is that

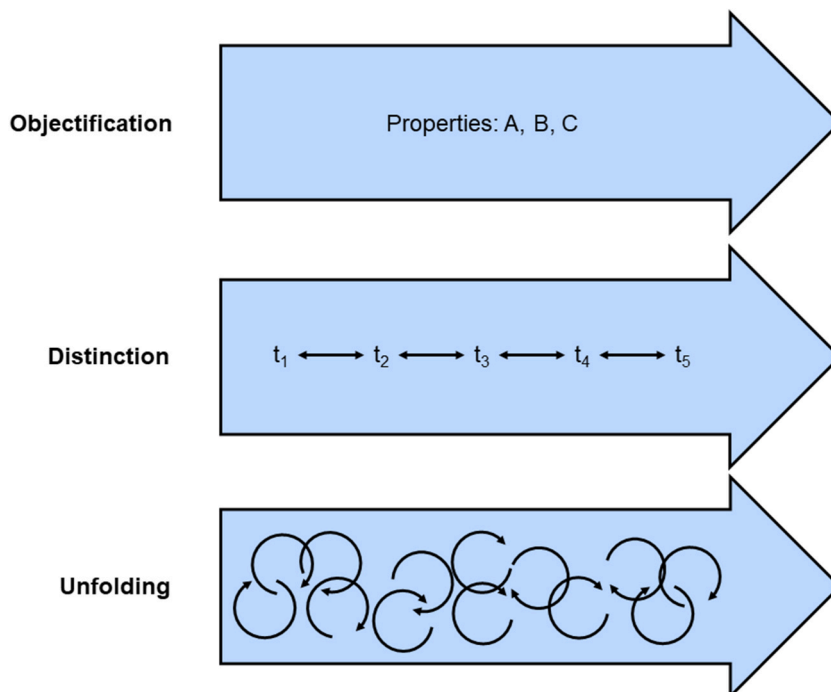


Fig. 3. Visualization of the three approaches to change.

development is influenced by an epigenetic landscape, which makes some pathways more likely than others. Steffen et al. [73] used a similar visualization to understand alternative pathways for climate change. In organization studies, moreover, scholars describe processes as multiplicities of paths [75], stressing the alternatives that actors have as they engage in organizational change.

4. Discussion

In this paper, we aim to sensitize scholars to different approaches to change. Our key contribution is the development of the ‘Iceberg Model of Change’, which includes the objectification, distinction, and unfolding approach. Fig. 3 provides a visualization of how each approach conceptualizes change. First, the *objectification approach* considers processes of change as ‘things’ to which properties can be assigned. Here, change is oftentimes treated as a symbolic object that can be used to steer societal discourse, emphasize the significance of work, or indicate thematic relationships across studies. Second, the *distinction approach* considers change as a series of states or phases of an entity or system, which facilitates comparisons of those states at different points in time. Third, the *unfolding approach* focuses on how change evolves, examining trajectories or the underlying mechanisms that interrelate in dynamic and complex ways. The overall contribution of our ‘Iceberg Model of Change’ is to make those approaches explicit.

Prior research has already presented multiple frameworks that help to conceptualize change. These frameworks include the ‘Three Phase Model’ [54] in social psychology, the ‘Motors of Change Framework’ [5] in organization studies, the ‘Theoretical Domains Framework’ in implementation science [40], system archetypes in system dynamics research [76], the ‘Advocacy Coalition Framework’ in policy science [77], or the ‘Driver-Pressure-State-Impact-Response Framework’ [72] in environmental science. Our ‘Iceberg Model of Change’ differs from most prior frameworks as it does not attempt to explain how change occurs (i.e., antecedents and outcomes, typical phases, or its internal mechanisms), but it strives to delineate different ways of conceptualizing change. Thus, it operates on an onto-epistemological level. We next discuss the implications of our work.

4.1. Implication 1: Enabling a comprehensive consideration of change

Our framework allows scholars to see change from different perspectives, which can enable a comprehensive consideration of focal change processes. Hughes et al. [4], for instance, primarily applied the *distinction approach* as they examined the impact of select heat waves on mass coral bleaching. We suggest that our framework could have helped those authors to consider additional aspects of coral bleaching. For instance, additionally focusing on the *objectification approach* could have enabled the authors to expand on the idea of coral bleaching as a matter for societal and political discourse (e.g., focusing on why coral bleaching is problematic and calling for specific initiatives). The authors conclude the paper with the statement that “[s]ecuring a future for coral reefs, including intensively managed ones such as the Great Barrier Reef, ultimately requires urgent and rapid action to reduce global warming” (p. 376). This statement could provide the baseline for calling in scholars and politicians to problematize coral bleaching more explicitly. Moreover, adopting the *unfolding approach* could have provided interesting extensions to this study. The authors stress various factors that matter for coral bleaching, such as cyclones, the role of marine park management and water quality maintenance, or the dynamic interplay of bleaching and recovery. Causal loop models could have enabled a better understanding of those complex interactions. It might also have been interesting to gain a better understanding of the unfolding of bleaching and recovery over time or the different trajectories of bleaching.

As this example shows, our model enables a comprehensive view of change in specific phenomena, such as coral bleaching. More generally speaking, scholars that typically focus on the *objectification approach*, for instance, risk overlooking the temporal progression of a focal change process as well as the complex underlying dynamics that constitute those processes. Scholars that typically adopt a *distinction approach*, by contrast, might miss the opportunity to use their focal change process symbolically, and they also undermine the complexity of causal mechanisms underpinning change. Scholars who focus on the *unfolding approach* might also miss the symbolic aspects of change processes, and thus opportunities to steer societal and political discourse. They might also struggle to identify phases through which change progresses.

Scholars can mitigate those risks by considering all three approaches that we identified in conjunction. Indeed, we do not consider the three approaches that we identified as distinct, but complementary and synergistic. The approaches may be seen as figure-ground inversions [75], in which specific aspects of change come to the foreground while others are moved to the background. Our framework articulates those approaches, enabling informed action related to processes of change.

4.2. Implication 2: Promoting interdisciplinary collaboration

Grand challenges, such as climate change, are often constituted through processes of change. Furthermore, interventions into grand challenges involve a need for change [78], for instance, when human behaviors should be changed to ensure human health. It is well-known that understanding and effectively tackling those grand challenges requires interdisciplinary collaboration [79–81], where interdisciplinarity is defined as “communication and collaboration across academic disciplines” [82, p. 44]. Different approaches to change, without awareness of differences in scholars’ assumptions, however, may hamper such interdisciplinary collaboration [83].

We argue that our framework can support interdisciplinary collaboration because it uncovers different approaches to change. Scholars can situate themselves in one approach and may begin to understand that their project partners differ in their assumptions. This way, our framework could be used to uncover diverging approaches to change across disciplines, enabling reflexive interdisciplinary collaboration. Our model contributes to the development of a common language (i.e., objectification, distinction, and

unfolding), which enables scholars to determine their focal approach, communicate it to others, and understand differences in assumptions.

Consider the following example. To understand and effectively tackle climate change, researchers from multiple disciplines need to collaborate [80]. Climate scientists assess how the climate changes in various regions, and they develop scenarios of future progression. To tackle climate change, however, a deep understanding of the organizational and societal practices that underpin this grand challenge is essential. Social scientists, thus, need to assess the practices that contribute to climate change, and how and why detrimental practices tend to persist. To better understand the interventions required to tackle climate change, political scientists may help understand intricate political dynamics and policy changes. To successfully study climate change in projects involving climate scientists, social scientists, and policy scholars, interdisciplinary teams must skillfully integrate the three approaches covered by our Iceberg Model of Change. For instance, the *objectification approach* can help to better understand how insights developed by climate and social scientists can enter the political arena as symbolic objects. The *distinction approach* can facilitate a good understanding of climate differences over time, and the *unfolding approach* helps to understand through which mechanisms the climate changes.

4.3. Implication 3: Supporting methodological reflexivity

Our framework also uncovers the need for methodological reflexivity [84,85]. Depending on which approach scholars adopt, they may be inclined to employ a different set of methods. In the *objectification approach*, for instance, scholars tend to consider change as either a dependent or independent variable, which allows them to understand its antecedents and consequences. This, for instance, suggests quantitative studies in which dependent and independent variables are measured and correlated [e.g., 86]. In the *distinction approach*, scholars compare the states of a change process at different points in time, for instance, by calculating differences (e.g., through statistical approaches that compare variables at different points in time) [e.g., 4]. In the *unfolding approach*, by contrast, scholars examine trends in the change process in line graphs (e.g., suggesting the continuous monitoring of a phenomenon) [e.g., 69] or identify underlying mechanisms (e.g., in longitudinal case studies) [e.g., 65].

Vice versa, the nature of available data may influence the approach that can be adopted. In a complex and dispersed change process, such as coral bleaching [4], for instance, it might be difficult to obtain detailed data about the unfolding of this process at scale. Similarly, it might not be feasible (or very resource-intensive) to continuously track the progression of a change process. Thus, scholars may only be able to obtain data at some points in time, which suggests a distinction approach. Certainly, methodological options and assumptions go hand in glove, but our framework enables reflexive decisions when it comes to empirical studies.

5. Avenues for future research

The central contribution of this paper is the development of the 'Iceberg Model of Change'. Even though we developed this conceptual model based on a literature review, the arguments on the applicability of this framework in specific research projects need to be examined, validated, and potentially refined empirically. Thus, the next step is the application and assessment of the framework in research collaborations.

We suggest that more research should be done to better conceptualize change. Questions for future research include: Which disciplines use the term change, and how does this relate to terms such as growth, decay, translation, transformation, transposition, development, transfer, innovation, flow, and flux? How do disciplinary backgrounds influence how scholars conceptualize change? Does this relate to reflexivity, and an awareness of the authors' roles in processes of change? Which methods are compatible with which approach, and what does methodological triangulation look like when approaches are integrated? Answering those and many other questions could enhance clarity related to the concept of change, and elucidate its underlying architecture.

CRediT authorship contribution statement

Christian A. Mahringer: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization, Writing – review & editing. **Laura Schmiedle:** Writing – original draft, Visualization, Software, Formal analysis, Writing – review & editing, Investigation, Methodology. **Lisa Albicker:** Writing – original draft, Investigation, Formal analysis, Writing – review & editing. **Simone Mayer:** Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization, Writing – review & editing.

Ethics declaration

Review and/or approval by an ethics committee and/or informed consent was not needed for this study because no empirical data have been used.

Data availability statement

The list of papers extracted from the 'Web of Science, Clarivate Analytics' database is available on request.

Declaration of AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ‘ChatGPT’ and ‘DeepL Write’ to check the text for spelling and grammatical mistakes. After using these tools, the authors reviewed and edited the content as needed and they take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Overview of phenomena related to change

In this appendix, we provide an overview of phenomena related to change. We identified five main topics, as illustrated in Fig. 2. We do not claim that these are all-encompassing, but the purpose of this analysis is to provide a high-level overview of phenomena in which change plays a role.

First, the green-colored nodes in the network hint at societal changes. Pandemics (such as COVID-19), for example, relate to diets, physical activity, mortality, and behavior more generally [87,88]. Human health is another phenomenon that relates to societal changes. Gut microbiota, for instance, influence diseases such as diabetes, and factors such as the use of antibiotics, dietary changes, and diabetes itself can cause changes in gut microbiota [89]. Therefore, it is important to understand these aspects to develop effective disease management strategies.

Second, the red-colored nodes relate to climate change and its impact on the environment. For instance, the development of climate change (e.g., rising temperatures) and its effects on agricultural ecosystems (e.g., changing precipitation patterns, droughts) influence the behavior and dynamics of insect pests, which has detrimental effects on agriculture [90], and thus food security. Furthermore, studies explore responses and the resilience of natural ecosystems to global warming and the associated climatic changes that have a significant impact on biodiversity [33].

Third, the blue-colored nodes relate to changes in land use. For instance, studies explore changes in spatial land patterns across China from woodland or grassland to agricultural and build-up land. Accelerated urbanization in China has led to an increase in build-up land used for construction purposes, indicating conflicts between urbanization and agricultural land conservation [91,92]. Furthermore, studies examine change processes resulting from urban challenges, such as the creation of housing areas [93]. Cities need to become smarter to cope with challenges arising from urbanization and improve resilience to withstand and recover from disruptive events [94].

Fourth, the yellow-colored nodes examine change processes related to the utilization of phase change materials (PCMs) in different sectors, such as biomedical, textile, or automotive industries [95]. Phase change materials are materials that contribute to the efficient use of waste heat and solar energy, fostering their performance [96]. Besides thermal energy storage, PCMs are also used in data processing. For instance, Zhang et al. [97] examine changes in computing devices, such as processing and memory units that involve phase changes, e.g., from amorphous to crystalline state and vice versa.

Fifth, the purple nodes in the network relate to initiatives and policies aimed at climate change adaptation and mitigation. Ocko et al. [98], for instance, discuss methane mitigation measures to slow global warming and to reduce associated damage to social and natural systems. Termeer et al. [99] discuss transformational change in response to climate change and examine how organizations can adapt to volatile dynamic environments. Furthermore, studies discuss the development of meaningful governance interventions to adapt to climate change. Schaffer et al. [100], for instance, compare the climate change policy output of several countries over time and discuss the extent to which differences in public demand for climate change mitigation lead to differences in public policy targeted at greenhouse gas mitigation.

References

- [1] G.S. Kirk, *Natural change in Heraclitus*, *Mind* 60 (237) (1951) 35–42.
- [2] S.V. Lynch, O. Pedersen, *The human intestinal microbiome in health and disease*, *N. Engl. J. Med.* 375 (24) (2016) 2369–2379.

- [3] V. Eyring, et al., Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization, *Geosci. Model Dev. (GMD)* 9 (5) (2016) 1937–1958.
- [4] T.P. Hughes, et al., Global warming and recurrent mass bleaching of corals, *Nature* 543 (7645) (2017) 373–377.
- [5] A.H. Van de Ven, M.S. Poole, Explaining development and change in organizations, *Acad. Manag. Rev.* 20 (3) (1995) 510–540.
- [6] C.B. Frey, M.A. Osborne, The future of employment: how susceptible are jobs to computerisation? *Technol. Forecast. Soc. Change* 114 (2017) 254–280.
- [7] S. Raoux, Phase change materials, *Annu. Rev. Mater. Res.* 39 (2009) 25–48.
- [8] D. Green, *How Change Happens*, Oxford University Press, 2016.
- [9] S. Puntambekar, Analyzing collaborative interactions: divergence, shared understanding and construction of knowledge, *Comput. Educ.* 47 (3) (2006) 332–351.
- [10] P.R. Carlile, A pragmatic view of knowledge and boundaries: boundary objects in new product development, *Organ. Sci.* 13 (4) (2002) 442–455.
- [11] L. Fleck, *Genesis and Development of a Scientific Fact*, University of Chicago Press, 1979.
- [12] B. Uzzi, et al., Atypical combinations and scientific impact, *Science* 342 (6157) (2013) 468–472.
- [13] S.-T.D. Yuan, et al., Customer engagement within multiple new media and broader business ecosystem—a holistic perspective, *Kybernetes* 46 (6) (2017) 1000–1020.
- [14] P. Kokol, K. Saranto, H. Blažun Vošner, eHealth and health informatics competences: a systemic analysis of literature production based on bibliometrics, *Kybernetes* 47 (5) (2018) 1018–1030.
- [15] G.R. Llanos-Herrera, J.M. Merigo, Overview of brand personality research with bibliometric indicators, *Kybernetes* 48 (3) (2018) 546–569.
- [16] N.J. Van Eck, L. Waltman, Citation-based clustering of publications using CitNetExplorer and VOSviewer, *Scientometrics* 111 (2017) 1053–1070.
- [17] F.J. van Rijnsvoever, (I can't get no) saturation: a simulation and guidelines for sample sizes in qualitative research, *PLoS One* 12 (7) (2017) e0181689.
- [18] S. Fuss, et al., Negative emissions—part 2: costs, potentials and side effects, *Environ. Res. Lett.* 13 (6) (2018) 063002.
- [19] B. Minasny, et al., Soil carbon 4 per mille, *Geoderma* 292 (2017) 59–86.
- [20] D.L. McCollum, et al., Energy investment needs for fulfilling the Paris agreement and achieving the sustainable development goals, *Nat. Energy* 3 (7) (2018) 589–599.
- [21] M. Springmann, et al., Options for keeping the food system within environmental limits, *Nature* 562 (7728) (2018) 519–525.
- [22] S.V. Feigin, et al., Proposed solutions to anthropogenic climate change: a systematic literature review and a new way forward, *Heliyon* 9 (10) (2023) e20544.
- [23] B.A. Swinburn, et al., The global syndemic of obesity, undernutrition, and climate change: the Lancet commission report, *Lancet* 393 (10173) (2019) 791–846.
- [24] S. Meerow, J.P. Newell, M. Stults, Defining urban resilience: a review, *Landsc. Urban Plann.* 147 (2016) 38–49.
- [25] C. Zarfl, et al., A global boom in hydropower dam construction, *Aquat. Sci.* 77 (2015) 161–170.
- [26] C. Lesk, P. Rowhani, N. Ramankutty, Influence of extreme weather disasters on global crop production, *Nature* 529 (7584) (2016) 84–87.
- [27] S. Rahmstorf, D. Coumou, Increase of extreme events in a warming world, *Proc. Natl. Acad. Sci. USA* 108 (44) (2011) 17905–17909.
- [28] R. Calantone, R. Garcia, C. Dröge, The effects of environmental turbulence on new product development strategy planning, *J. Prod. Innovat. Manag.* 20 (2) (2003) 90–103.
- [29] A.A. de Souza Machado, et al., Microplastics as an emerging threat to terrestrial ecosystems, *Global Change Biol.* 24 (4) (2018) 1405–1416.
- [30] S. Gössling, D. Scott, C.M. Hall, Pandemics, tourism and global change: a rapid assessment of COVID-19, *J. Sustain. Tourism* 29 (1) (2020) 1–20.
- [31] P. Pyšek, et al., Scientists' warning on invasive alien species, *Biol. Rev.* 95 (6) (2020) 1511–1534.
- [32] E.A. Schuur, et al., Climate change and the permafrost carbon feedback, *Nature* 520 (7546) (2015) 171–179.
- [33] G.T. Pecl, et al., Biodiversity redistribution under climate change: impacts on ecosystems and human well-being, *Science* 355 (6332) (2017) 1–9.
- [34] J.T. Abatzoglou, A.P. Williams, Impact of anthropogenic climate change on wildfire across western US forests, *Proc. Natl. Acad. Sci. USA* 113 (42) (2016) 11770–11775.
- [35] M.C. Urban, Accelerating extinction risk from climate change, *Science* 348 (6234) (2015) 571–573.
- [36] S.T. Pickett, M.L. Cadenasso, B. McGrath, *Resilience in Ecology and Urban Design: Linking Theory and Practice for Sustainable Cities*, Springer Science & Business Media, 2013.
- [37] J.A. Foley, et al., Global consequences of land use, *Science* 309 (5734) (2005) 570–574.
- [38] M. Luck, J. Wu, A gradient analysis of urban landscape pattern: a case study from the phoenix metropolitan region, Arizona, USA, *Landsc. Ecol.* 17 (2002) 327–339.
- [39] N. Brenner, C. Schmid, Towards a new epistemology of the urban? *City* 19 (2–3) (2015) 151–182.
- [40] L. Atkins, et al., A guide to using the theoretical domains framework of behaviour change to investigate implementation problems, *Implement. Sci.* 12 (1) (2017) 1–18.
- [41] C.E. Helfat, J.A. Martin, Dynamic managerial capabilities: review and assessment of managerial impact on strategic change, *J. Manag.* 41 (5) (2015) 1281–1312.
- [42] K. Szóts-Kováts, C. Kiss, How job crafting is related to the individual readiness to organizational change, *Heliyon* 9 (4) (2023) e15025.
- [43] F. Sánchez-Bayo, K.A. Wyckhuys, Worldwide decline of the entomofauna: a review of its drivers, *Biol. Conserv.* 232 (2019) 8–27.
- [44] J. Huisman, et al., Cyanobacterial blooms, *Nat. Rev. Microbiol.* 16 (8) (2018) 471–483.
- [45] J.O. Oti, A.T. Kabo-Bah, E. Ofosu, Hydrologic response to climate change in the densu river basin in Ghana, *Heliyon* 6 (8) (2020) e04722.
- [46] M. Khairulbahri, Analyzing the impacts of climate change on rice supply in West Nusa Tenggara, Indonesia, *Heliyon* 7 (12) (2021) e08515.
- [47] J.T. Kerr, et al., Climate change impacts on bumblebees converge across continents, *Science* 349 (6244) (2015) 177–180.
- [48] D. Acemoglu, P. Restrepo, Automation and new tasks: how technology displaces and reinstates labor, *J. Econ. Perspect.* 33 (2) (2019) 3–30.
- [49] J. Chen, et al., Effects of technological changes on China's carbon emissions, *Technol. Forecast. Soc. Change* 153 (2020) 119938.
- [50] S.M. Chege, D. Wang, The influence of technology innovation on sme performance through environmental sustainability practices in Kenya, *Technol. Soc.* 60 (2020) 101210.
- [51] R. Agarwal, et al., Research commentary: the digital transformation of healthcare: current status and the road ahead, *Inf. Syst. Res.* 21 (4) (2010) 796–809.
- [52] B. Neumann, et al., Future coastal population growth and exposure to sea-level rise and coastal flooding—a global assessment, *PLoS One* 10 (3) (2015) e0118571.
- [53] K.A. Cradock, et al., Behaviour change techniques targeting both diet and physical activity in type 2 diabetes: a systematic review and meta-analysis, *Int. J. Behav. Nutr. Phys. Activ.* 14 (1) (2017) 1–17.
- [54] K. Lewin, *Frontiers in group dynamics: concept, method and reality in social science; social equilibria and social change*, *Hum. Relat.* 1 (1) (1947) 5–41.
- [55] E. Kübler-Ross, *On Death and Dying*, Collier Books/Macmillan Publishing Co, 1970.
- [56] J.P. Kotter, Leading change: why transformation efforts fail, *Harv. Bus. Rev.* March–April (1995) 59–67.
- [57] D.G. Angeler, et al., Quantifying the adaptive cycle, *PLoS One* 10 (12) (2015) e0146053.
- [58] H. Wang, et al., Global, regional, and national life expectancy, all-cause mortality, and cause-specific mortality for 249 causes of death, 1980–2015: a systematic analysis for the global burden of disease study 2015, *Lancet* 388 (10053) (2016) 1459–1544.
- [59] X.-P. Song, et al., Global land change from 1982 to 2016, *Nature* 560 (7720) (2018) 639–643.
- [60] C. Homer, et al., Completion of the 2011 national land cover database for the conterminous United States—representing a decade of land cover change information, *Photogramm. Eng. Rem. Sens.* 81 (5) (2015) 345–354.
- [61] R.J. Keenan, et al., Dynamics of global forest area: results from the FAO global forest resources assessment 2015, *For. Ecol. Manag.* 352 (2015) 9–20.
- [62] C. Torres-Martín, et al., Implementation of the flipped classroom and its longitudinal impact on improving academic performance, *Educ. Technol. Res. Dev.* 70 (3) (2022) 909–929.
- [63] T. Hernes, *Understanding Organization as Process. Theory for a Tangled World*, Routledge, 2008.
- [64] A.N. Whitehead, *Process and reality. An Essay in Cosmology*, The Free Press, 1978.

- [65] F. Deken, et al., Generating novelty through interdependent routines: a process model of routine work, *Organ. Sci.* 27 (3) (2016) 659–677.
- [66] R. Seidl, et al., Forest disturbances under climate change, *Nat. Clim. Change* 7 (2017) 395–402.
- [67] Z. Younsi, H. Naji, Numerical simulation and thermal performance of hybrid brick walls embedding a phase change material for passive building applications, *J. Therm. Anal. Calorim.* 140 (3) (2020) 965–978.
- [68] W. Steffen, et al., The trajectory of the anthropocene: the great acceleration, *The Anthropocene Review* 2 (1) (2015) 81–98.
- [69] J.-F. Pekel, et al., High-resolution mapping of global surface water and its long-term changes, *Nature* 540 (7633) (2016) 418–422.
- [70] J.W. Forrester, System dynamics, systems thinking, and soft or, *Syst. Dynam. Rev.* 10 (2–3) (1994) 245–256.
- [71] L. Baugh Littlejohns, et al., The value of a causal loop diagram in exploring the complex interplay of factors that influence health promotion in a multisectoral health system in Australia, *Health Res. Pol. Syst.* 16 (1) (2018) 126.
- [72] B. Ness, S. Anderberg, L. Olsson, Structuring problems in sustainability science: the multi-level DPSIR framework, *Geoforum* 41 (3) (2010) 479–488.
- [73] W. Steffen, et al., Trajectories of the earth system in the anthropocene, *Proc. Natl. Acad. Sci. USA* 115 (33) (2018) 8252–8259.
- [74] C.H. Waddington, Canalization of development and the inheritance of acquired characters, *Nature* 150 (3811) (1942) 563–565.
- [75] B.T. Pentland, et al., Process multiplicity and process dynamics: weaving the space of possible paths, *Organization Theory* 1 (3) (2020) 1–21.
- [76] P. Checkland, *Systems Thinking, Rethinking Management Information Systems*, 1999, pp. 45–56.
- [77] P.A. Sabatier, C.M. Weible, The advocacy coalition framework: innovations and clarifications, in: *Theories of the Policy Process*, second ed., Routledge, 2019.
- [78] K. Sele, et al., We are all pattern makers! How a flat ontology connects organizational routines and grand challenges, *Strat. Organ.* 22 (3) (2024) 530–549.
- [79] G. Carr, D.P. Loucks, G. Blöschl, Gaining insight into interdisciplinary research and education programmes: a framework for evaluation, *Res. Pol.* 47 (1) (2018) 35–48.
- [80] B. König, et al., A framework for structuring interdisciplinary research management, *Res. Pol.* 42 (1) (2013) 261–272.
- [81] G.S. Omenn, Grand challenges and great opportunities in science, technology, and public policy, *Science* 314 (5806) (2006) 1696–1704.
- [82] J.A. Jacobs, S. Frickel, Interdisciplinarity: a critical assessment, *Annu. Rev. Sociol.* 35 (1) (2009) 43–65.
- [83] C.A. Mahringer, et al., Benefits and obstacles of interdisciplinary research: insights from members of the young Academy at the Heidelberg Academy of sciences and Humanities, *iScience* 26 (12) (2023).
- [84] C. Kingdon, Reflexivity: not just a qualitative methodological research tool, *Br. J. Midwifery* 13 (10) (2005) 622–627.
- [85] M. Alvesson, K. Skoldberg, *Reflexive Methodology: New Vistas for Qualitative Research*, Sage, 2017.
- [86] J. Lelieveld, et al., The contribution of outdoor air pollution sources to premature mortality on a global scale, *Nature* 525 (7569) (2015) 367–371.
- [87] J. Faulkner, et al., Physical activity, mental health and well-being of adults during initial COVID-19 containment strategies: a multi-country cross-sectional analysis, *J. Sci. Med. Sport* 24 (4) (2021) 320–326.
- [88] T. Arora, I. Grey, Health behaviour changes during COVID-19 and the potential consequences: a mini-review, *J. Health Psychol.* 25 (9) (2020) 1155–1163.
- [89] J. Durack, S.V. Lynch, The gut microbiome: relationships with disease and opportunities for therapy, *J. Exp. Med.* 216 (1) (2019) 20–40.
- [90] T. Payn, et al., Changes in planted forests and future global implications, *For. Ecol. Manag.* 352 (2015) 57–67.
- [91] H. Dadashpoor, P. Azizi, M. Moghadas, Land use change, urbanization, and change in landscape pattern in a metropolitan area, *Sci. Total Environ.* 655 (2019) 707–719.
- [92] X. Deng, et al., Impact of urbanization on cultivated land changes in China, *Land Use Pol.* 45 (2015) 1–7.
- [93] C. Haaland, C.K. van Den Bosch, Challenges and strategies for urban green-space planning in cities undergoing densification: a review, *Urban For. Urban Green.* 14 (4) (2015) 760–771.
- [94] P.J.G. Ribeiro, L.A.P.J. Gonçalves, Urban resilience: a conceptual framework, *Sustain. Cities Soc.* 50 (2019) 101625.
- [95] K. Pielichowska, K. Pielichowski, Phase change materials for thermal energy storage, *Prog. Mater. Sci.* 65 (2014) 67–123.
- [96] D. Feng, et al., Review on nanoporous composite phase change materials: fabrication, characterization, enhancement and molecular simulation, *Renew. Sustain. Energy Rev.* 109 (2019) 578–605.
- [97] W. Zhang, et al., Designing crystallization in phase-change materials for universal memory and neuro-inspired computing, *Nat. Rev. Mater.* 4 (3) (2019) 150–168.
- [98] I.B. Ocko, et al., Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming, *Environ. Res. Lett.* 16 (5) (2021) 054042.
- [99] C.J. Termeer, A. Dewulf, G.R. Biesbroek, Transformational change: governance interventions for climate change adaptation from a continuous change perspective, *J. Environ. Plann. Manag.* 60 (4) (2017) 558–576.
- [100] L.M. Schaffer, B. Oehl, T. Bernauer, Are policymakers responsive to public demand in climate politics? *J. Publ. Pol.* 42 (1) (2022) 136–164.